WIMS-IST/DRAGON-IST SIDE-STEP CALCULATION OF REACTIVITY DEVICE AND STRUCTURAL MATERIAL INCREMENTAL CROSS SECTIONS FOR WOLSONG NPP UNIT 1

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Abstract

This paper describes the calculation of two-group incremental cross sections for all of the reactivity devices and in-core structural materials for an RFSP-IST full-core model of Wolsong NPP Unit 1, in support of the conversion of the reference plant model to two energy groups. This is of particular interest since the calculation used the new standard "side-step" approach, which is a three-dimensional supercell method that employs the Industry Standard Toolset (IST) codes DRAGON-IST and WIMS-IST with the ENDF/B-VI nuclear data library. In this technique, the macroscopic cross sections for the fuel regions and the device material specifications are first generated using the lattice code WIMS-IST with 89 energy groups. DRAGON-IST then uses this data with a standard supercell modelling approach for the three-dimensional calculations.

Incremental cross sections are calculated for the stainless-steel adjuster rods (SS-ADJ), the liquid zone control units (LZCU), the shutoff rods (SOR), the mechanical control absorbers (MCA) and various structural materials, such as guide tubes, springs, locators, brackets, adjuster cables and support bars and the moderator inlet nozzle deflectors. Isotopic compositions of the Zircaloy-2, stainless steel and Inconel X-750 alloys in these items are derived from Wolsong NPP Unit 1 history dockets. Their geometrical layouts are based on applicable design drawings. Mid-burnup fuel with no moderator poison was assumed. The incremental cross sections and key aspects of the modelling are summarized in this paper.

1. Introduction

1.1 Objective and Background

Presented here is the full set of two-energy-group reactivity device and structural material incremental cross sections, required for a Wolsong Nuclear Power Plant (NPP) Unit 1 full-core equilibrium neutronics model, computed using the "side-step" approach with the current Industry Standard Toolset (IST) versions of the lattice codes WIMS-AECL [1] and DRAGON [2]. This work was done by AECL in support of the update of Wolsong NPP Unit 1 operational analysis models to 2 energy groups.

1.2 Overall Simulation Approach

The standard Canadian approach to full-core neutronics analysis uses the computer programs WIMS-IST, DRAGON-IST and RFSP-IST [3] with 2 energy groups. This approach is also being adopted for CANDU® analysis in Korea [4][5].

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The current POWDERPUFS-V-based full-core physics models used for Unit 1 operations are not full 2-group models and employ reactivity-device and structural-material incremental cross sections that were calculated using MULTICELL and POWDERPUFS-V [6][7]. These incremental cross sections are re-calculated here in 2 energy groups using the WIMS-IST/DRAGON-IST "side-step" methodology, which is based on References [8] and [9].

A WIMS-IST model is prepared using input parameters for 37-element natural-uranium fuel from a reference full-core operational-physics model, without accounting for diametral pressure tube creep due to irradiation. This model is used as the basis of the WIMS-IST calculations that provide material cross sections for use by DRAGON-IST.

Material physical and geometrical properties required by WIMS-IST and DRAGON-IST are assumed to correspond to fresh cold materials. As a result, plant design and construction data are used to derive these properties. Using such data, a DRAGON-IST calculation of incremental cross sections is prepared for each desired in-core item, assuming mid-burnup fuel and no moderator poison.

2. Numerical Methods

2.1 Computer Programs

The lattice cell code WIMS-IST is a two-dimensional multi-group neutron-transport code. This IST version of WIMS-AECL is version 2.5d with ENDF/B-VI version 1a nuclear data library in 89 energy groups. Recent validation of this computer program as a lattice code for CANDU plants is reported in References [10] and [1].

The neutron-transport code DRAGON-IST provides a deterministic solution of the neutron-transport equation in nuclear-reactor lattices. This IST version of DRAGON is version 3.04Bb, which is used mainly to perform three-dimensional (3D) supercell calculations for CANDU reactors. A supercell represents a generic piece of the reactor core, of specific size and shape, which consists of fuel, moderator, reactivity devices, fuel channel and reactor hardware. The modelling of CANDU reactivity devices, which are perpendicular to the fuel channels, requires the 3D approach. The DRAGON-IST neutron-transport code itself is designed for general geometry and can perform lattice-cell calculations for both CANDU clusters and PWR assemblies. It is capable of solving one-dimensional, two-dimensional, and three-dimensional problems, for individual lattice cells or for supercell configurations. Further details of its capabilities may be found in the code documentation [2].

The following advantages of DRAGON-IST make it an excellent choice as a standard three-dimensional supercell code for CANDU analysis:

1. The DRAGON-IST multigroup neutron-transport method is theoretically rigorous, relatively straightforward, and consistent with the WIMS-IST lattice-cell calculations.
2. It has either an exact or a nearly exact geometrical representation of the devices and the fuel channels.
3. The results of the various benchmark comparisons are all within acceptable ranges.

Validation of the "All-DRAGON" or "solo" method was reported in Reference [11]. The more recent qualification of DRAGON-IST in "side-step" with WIMS-IST, described below, is compared to the "solo" method in Reference [12] and validation of the "side-step" method is reported in References [9] and [13]. Further development of the DRAGON code for advanced CANDU applications is described in References [14], [15] and [16].

2.2 The "Side-Step" Approach

The "side-step" method of calculating incremental cross sections is outlined in Figure 1. The DRAGON-IST supercell calculation requires macroscopic cross sections that represent materials in fuel channels and reactivity devices. Those macroscopic cross sections are produced by homogenization from a two-dimensional WIMS-IST lattice-cell calculation using 89 energy groups. The T16MAC auxiliary code [12] reads the 'Tape16' files produced by WIMS-IST, performs homogenization, and prepares the resultant cross sections in the form of a MACROLIB data file to be read by the subsequent DRAGON-IST 89-group supercell calculation.

2.3 The Supercell Calculation

In the standard supercell calculation of CANDU reactivity device and structural material macroscopic cross sections, the device or hardware is located between two fuel bundles in the supercell geometry configuration as shown in Figure 2. The macroscopic cross sections that characterize each region in the model are those supplied by the T16MAC auxiliary code. The macroscopic cross sections generated using DRAGON-IST are homogenized by smearing them over the region represented by the inner 1-lattice-pitch of the supercell, so that they can be applied to the same-size region in RFSP-IST. The homogenized volume is illustrated in Figure 3. All cross sections are condensed to two energy-groups with the two-group energy boundary at 0.625 eV.

DRAGON-IST does not model cluster geometry in a 3D model [15]. As a result, a device is either explicitly represented, as is the adjuster, or homogenized into concentric annuli, as are the liquid zone control units. For the calculation of properties of structural materials in the reflector or on the calandria shell, the standard supercell model, with two neighbouring fuel channels, is useful to increase the number of neutrons around the material so as to provide a higher precision calculation. These modelling approximations are considered sufficient for the calculation of incremental cross sections.

2.4 Calculation of the Incremental Cross Sections

For most devices or structural materials, two supercell calculations are performed: one with the device included in the model and without the device. The difference between the two resultant sets of homogenized macroscopic cross sections give the incremental cross sections. In the special case of the liquid zone control units, the incremental cross sections are separately generated for the empty zone control unit and for the full-minus-empty zone control unit.

3. Reference WIMS-IST Model

The reference WIMS-IST model is the basis of the unit cell calculation used to generate material cross sections for DRAGON-IST. This model is essentially a conversion of the reference POWDERPUFS-V model with equilibrium-core lattice conditions, to a WIMS-IST model following as closely as possible the validated CANDU modelling approach from Reference [10].

3.1 The Bare Lattice

A standard CANDU 6 lattice cell contains a 37-element natural-uranium bundle of length 49.53 cm and pressurized heavy-water coolant in a pressure tube enclosed within a calandria tube. A one-lattice-pitch (28.575 cm) square region of unpressurized heavy water (moderator) at a significantly lower temperature surrounds this calandria tube. The bare lattice cell geometry used in the reference WIMS-IST model for Wolsong NPP Unit 1 is illustrated in Figure 4. Table 1 gives key fuel and reactor data for the bare lattice.

3.2 Fuel Data

The fuel bundle is assumed to have a fuel density of 10.62 g/cm^3 UO_2, consistent with current production. For the purposes of the WIMS-IST model, the fuel is assumed to be at the reference temperature of 687ºC. Although the fuel density varies slightly with irradiation, temperature and initial density, the overall effect is assumed to be negligible. Inter-pellet gaps will reduce the UO_2 density along an element from the nominal value for each pellet. The homogenized density is taken to be slightly more than 1% below the nominal density in Table 1.

The sheath outer diameter is reduced by about 1% from Table 1, while preserving Zircaloy-4 volume, to account for its collapse onto the pellet after a short period of operation under hot conditions.

3.3 Model Geometry

The core-average nominal thermally crept inner and outer pressure-tube radii are taken as 5.179 cm and 5.613 cm, respectively. These values are derived assuming that the change in the pressure tube density and the diametral creep effects of pressure can be regarded as negligible. The radius of the mesh circle half way between the inner and outer pressure-tube surfaces is assumed to expand from room temperature to the operating temperature by about 0.183% [17]. When similar assumptions are made for the calandria tube, its core-average nominal thermally-crept inner and outer radii are taken to be 6.450 cm and 6.590 cm, respectively.

4. The DRAGON-IST Model

4.1 Wolsong NPP Unit 1 In-Core Materials

The reactivity devices for which neutronic incremental cross sections are calculated include the stainless-steel adjuster rods (ADJ), the liquid zone control units (LZCUs), the shutoff rods (SOR) and the mechanical control absorbers (MCA). The incremental cross sections are also calculated for the guide tubes associated with these devices, as well as the in-core flux detector guide tubes and poison-injection nozzles. The following structural materials are also simulated: adjuster support bars and cables, guide-tube brackets and locators, guide-tube tensioning springs and coupling nuts, and moderator inlet nozzle deflectors.

Nominal dimensions were used from relevant design drawings. The chemical compositions of the zirconium alloys, stainless steel and inconel nickel were assumed to be consistent with ASTM specifications and pre-installation material assays, where available from history dockets provided by KHNP. All zirconium alloys considered here are assumed to have a nominal density of 6.55 g/cm^3 at room temperature, with small reductions at higher temperatures. A nominal stainless steel density of 7.988 g/cm^3 is assumed. This was originally used in manufacturing feedback calculations for the adjusters and is consistent with the typical range of stainless steel densities around the time of Wolsong NPP Unit 1 commissioning. Inconel X-750 is assumed to have a nominal density of about 8.25 g/cm^3.

4.2 Reactivity Devices

4.2.1 Adjuster Rods

The stainless-steel adjusters are composed of a shim rod inside a cylindrical tube. There are 6 types of rods with various combinations of shim rod radius and tube thickness. The tube external radius of all the adjusters is constant. This data is taken from unpublished analysis that was done to provide feedback at the time of rod construction. That analysis indicated that a variation of up to 0.01 cm in the radius of a shim rod changed its reactivity worth by no more than 0.025%. For comparison, the design tolerance is about 0.006 cm.

Due to the concentric arrangement of the rods and tubes, no geometric approximations are required with DRAGON-IST. The adjusters are represented as an inner region of stainless steel, surrounded by a heavy-water moderator region, another stainless steel region, and another heavy-water moderator region, all surrounded by a Zircaloy-2 guide tube.

4.2.2 Liquid Zone Control Units

The liquid zone control system has two groups of seven compartments in six different vertical Zircaloy-2 tubes (the LZCUs). Light-water absorber fills each compartment to varying levels during reactor operation. There are two sizes of LZCU. The longer LZCUs have three compartments each (top = “Type32”, middle = “Type21”, and bottom = “Type

10”) and reside in the centre of the core. The shorter LZCUs have two compartments each (top = “Type 21”, and bottom = “Type 10”). There are various numbers of feeder, scavenger, bubbler and balance tubes inside each “Type” of compartment.

The LZCU geometry is more complex than that of adjuster rods. Because DRAGON-IST does not allow cluster geometry in a 3D model, the exact cluster geometry is used in WIMS-IST. The corresponding homogenized material is then implemented as an equivalent solid device in the supercell calculation. The WIMS-IST model used to generate this homogenised material is shown in Figure 5. Validation of this approach is given in Reference [18].

4.2.3 Mechanical Control Absorbers and Shutoff Rods

The shutoff rods and mechanical control absorbers are physically the same and are composed of a cadmium tube sandwiched between two stainless steel tubes. As a result, the MCAs and SORs are represented by an inner region of heavy-water moderator surrounded by a number of concentric regions: a stainless-steel region, a cadmium region, another stainless-steel region, and another heavy-water moderator region, all surrounded by a Zircaloy-2 guide tube.

The cadmium is represented by Cd-113 isotope alone because it is the only significant absorber isotope. An equivalent Cd-113 density of 1.07 g/cm^3 is then calculated using following equation:

$$\rho_{Cd-113} = \rho_{Cd} F_{Cd-113} \frac{M_{Cd-113}}{M_{Cd}}$$

with values taken from Reference [19]:

ρ_{Cd-113} is the equivalent density of Cd-113 (g/cm^3);

ρ_{Cd} is the density of cadmium (8.69 g/cm^3);

F_{Cd-113} is the natural abundance of Cd-113 in cadmium (12.22 atom %);

M_{Cd-113} is the isotopic mass of Cd-113 (112.904401 amu);

M_{Cd} is the isotopic mass of natural cadmium (112.411 amu).

The typical Cd purity of 99.9% has no significant effect on these results. A longitudinal gap of up to 0.635 cm (¼") is allowed for in the cadmium sheet after swaging. This represents a further density reduction of up to 1.8%, so that the equivalent Cd-113 density is 1.05 g/cm^3.

In the reference design drawings, a radial gap also exists between the stainless steel tubes and the Cd sheet before swaging. Prior to swaging, the Cd sheet is rolled around the inner stainless steel tube and then fitted inside the outer tube. The swaging process then expands the inner tube and the Cd, so as to push out the air gap between the Cd and the two stainless-steel tubes. However, this does not change the thickness of the cadmium sheet. The DRAGON-IST model assumes pre-swaging inner stainless-steel tube dimensions, but assumes the cadmium sheet is pressed up against the outer stainless steel tube. Instead of modelling a very small air gap plus very thin cadmium sheet, the Cd-113 is ‘smeared’ between the inner and outer stainless steel tubes by assuming the entire gap between tubes is filled with this nuclide and by reducing its density accordingly to 0.594 g/cm^3.

4.2.4 Guide Tubes

The guide tube incremental cross sections for the adjuster and SOR/MCA are calculated at the same time as the respective device properties. The incremental cross sections are independently calculated for LZCU bottom guide tubes, horizontal flux detector (HFD) guide tubes, vertical flux dectectors (VFD) guide tubes and poison injection nozzles. Detector guide tubes are taken to consist of both the detector capsule tube and the outer guide tube extension.* The region between the HFD tubes is filled with helium, while the inter-tube region is filled with heavy water for the VFDs.

The guide tubes are composed of Zircaloy-2. Further, the adjuster and SOR/MCA guide tubes, the LZCU bottom guide tubes and the poison injection nozzles are perforated. This is accounted for by modelling the Zircaloy-2 material as being diluted with heavy water, where necessary.

4.3 Structural Material

Each adjuster has a support bar and a cable connected to its drive mechanism, both composed of stainless steel. Only adjuster supporting bars and cables incremental cross sections are calculated, as no other control rods are maintained in the core for normal steady-state operation. These are modelled explicitly with DRAGON-IST.

Each guide tube is secured at its bottom or end with a locator and a bracket. These guide tubes include those for the adjusters, the bottoms of the liquid zone control assemblies, the SOR’s/MCA’s, the VFD’s and the HFD’s, as well as the poison injection nozzles. The locator and bracket incremental cross sections are assumed to be identical for all such materials and are assumed to be uniformly composed of stainless steel. The mass of a combined bracket/locator is assumed to be consistent with past experience. The small effect of the Zircaloy-2 material in the locator coupling rod is not explicitly accounted for in this model. An “equivalent” plain rod of 28.575 cm height with a radius that preserves the overall material volume is used in the DRAGON-IST model.

Tensioning spring and coupling nuts are located at the bottoms of adjuster rods, LZCUs and SOR/MCA rods. Coupling nuts are composed of stainless steel, while tensioning springs are made of Inconel X-750. Each spring is concentric with a locator coupling rod that is composed of Zircaloy-2. The coupling nuts also surround the Zircaloy-2 tube. In the supercell, the tensioning spring is modelled as

* The detector capsule resides within the guide tube extension, which is a larger-diameter tube than the bottom/end portion of the guide tube.

two concentric tubes, the inside tube material is Zircaloy-2 while the outside tube is composed of Inconel X-750. A small ring of moderator separates the tubes. In the case of the LZCUs, a small hole, which is filled with moderator, is accounted for inside the Zircaloy-2 coupling rod.

The coupling nuts are modelled in the same manner. In this case, two tubes are used. The inside tube is composed of Zircaloy-2 and the outside one is composed of stainless steel.

The moderator inlet nozzle deflectors are composed of stainless steel, with a height of about 43 cm and occupying a total volume of close to 3000 cm^3. To compute the total volume, the inlet nozzles were split into different components: Front Plate, Back Plate, Dividers, Side Plate and Bracket. The same DRAGON-IST modelling approach is used as for the combined bracket/locator: an equivalent plain rod of 28.575 cm height represents the deflector, with an equivalent radius to preserve the material volume.

4.4 Flux Calculation

For the adjusters and LZCUs, a homogeneous B_1 leakage model is used with an imposed k_{eff} =1 to simulate a critical supercell because these devices are used to maintain the reactor in a critical state.

For the SOR/MCAs, the absorber rods are inserted into the core to make it highly sub-critical. From a physical point of view, a critical flux spectrum would then not be representative of the core state for the evaluation of incremental cross sections associated with these reactivity devices. One alternative is to solve the flux equation without leakage. This is the approach chosen here. However, the use of one or the other option doesn't affect significantly the device reactivity worth when the incrementals are applied in RFSP-IST.

4.5 Spatial Homogenization

All the incremental cross sections presented in this report were homogenized over 1 lattice pitch × 1 lattice pitch × 1 bundle length. When directly applying the incremental cross sections in RFSP-IST, the device or structural material dimensions should normally be input with dimensions 1 lattice pitch × 'actual y-length' × 1 bundle length if they are vertical, or with dimensions 'actual x-length' × 1 lattice pitch × 1 bundle length if they are horizontal. However, if instead of 1 bundle length the z-width in RFSP-IST is Δz then the incrementals should be modified by a factor of 49.53 cm / Δz.

The only exception to the above is the moderator inlet nozzle deflector, which is modelled as a vertical device. In the past, this has been modelled in RFSP-IST as a rectangular cell of dimensions 'actual x-width' × 1 lattice pitch × 1 bundle length, where the 'actual x-width' is the full x-extension of the deflector. In reality, each deflector has a fan shape that extends almost 2 lattice pitches in both the y- and z-directions. Also, the main structure is tilted a few degrees from the vertical, with a small bracket that attaches it to the calandria wall (e.g., see Figure 6). To apply the calculated incrementals, this device may be represented in RFSP-IST by a single rectangular cell with dimensions:

'actual x-width' × 'modelled y-height' × 1 bundle length

In this case, the incremental cross sections should be increased by a factor of:

$$\frac{28.575\ \text{cm}}{\text{'actual } x\text{ - width'}},$$

to account for volume weighting in the x-direction. There is no volume weighting in the y-direction, since the 'modelled y-height' is used.

5. Key Results

5.1 Incremental Cross Sections

A full set of incremental properties was calculated for each in-core item. For example, the incremental thermal absorption cross sections for in-core reactivity devices and structural materials with mid-burnup fuel and no moderator poison are given in Tables 2 to 6. Table 2 gives this data for adjuster-rod cells. Table 3 gives the values for empty and full-minus-empty zone-control-unit cells for each of the compartment types. Table 4 gives the values for the mechanical control absorbers and shutoff rods. Tables 5 and 6 give the values for the guide tubes and structural materials, respectively.

The full set of incremental properties for each in-core item included the following:

$\Delta\Sigma_{tr1}$: incremental fast transport cross section (cm^{-1});

$\Delta\Sigma_{tr2}$: incremental thermal transport cross section (cm^{-1});

$\Delta\Sigma_{a1}$: incremental fast absorption cross section (cm^{-1});

$\Delta\Sigma_{a2}$: incremental thermal absorption cross section (cm^{-1});

$\Delta\nu\Sigma_{f1}$: incremental fast yield cross section (cm^{-1});

$\Delta\nu\Sigma_{f2}$: incremental thermal yield cross section (cm^{-1});

$\Delta\Sigma_{s1\rightarrow2}$: incremental scattering cross section from group 1 to group 2 (cm^{-1});

$\Delta\Sigma_{s2\rightarrow1}$: incremental scattering cross section from group 2 to group 1 (cm^{-1});

ΔH_1: incremental group 1 H-factor (10^{-11}kW cm^2 s /bundle);

ΔH_2: incremental group 2 H-factor (10^{-11}kWcm^2 s /bundle); and

ΔF: incremental F-factor.

The incremental transport cross sections are defined as:

$$\Delta\Sigma_{tr} = \frac{1}{3D^{rodded}} - \frac{1}{3D^{unrodded}}$$

where D^{rodded} and $D^{unrodded}$ are the diffusion coefficients for the case where the device is inserted and the case without the device respectively. Since DRAGON-IST does not calculate H-factors automatically, the H-factor and its incremental were calculated using the following equations:

$$H_{g,cell} = 10^8 V_{bundle} \Sigma_{f,g,cell} E_f$$

$$\Delta H_g = H_{g,cell} \frac{\Delta\Sigma_{f,g}}{\Sigma_{f,g,cell}}$$

with the following definitions:

V_{cell}: volume of a single fuel lattice-cell (cm^3);

E_f: energy released per fission (Joules);

$\Sigma_{f,g,cell}$: cell averaged g-group fission cross section (cm^{-1}); and

$\Delta\Sigma_{f,g}$: incremental for g-group fission cross section (cm^{-1}).

6. Conclusion

The incremental cross sections presented here for Wolsong NPP Unit 1 reactivity devices, adjuster rods, the liquid zone controllers, the shutoff rods, the mechanical control absorbers and various structural materials have been uniformly generated with the WIMS-IST/DRAGON-IST side-step method.

7. References

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Table 1
Data f or Bare Lattice

Lattice pitch	28.575	cm (square)
Bundle length	49.53	cm
Moderator (and reflector) temperature volumetric average	69	°C
Moderator (and reflector) D_2O purity	99.85	wt %
Coolant temperature averaged over channel	288	°C
Coolant D_2O purity	99.10	wt %
Pressure tube (Zr-2.5% Nb) inside diameter	10.3378	cm
Average pressure tube wall thickness	0.4343	cm
Calandria tube (Zr-2) inside diameter	12.8956	cm
Average calandria tube wall thickness	0.1397	cm
Bundle design	37-element	UO_2
Ring 1 (inner) elements pitch circle diameter	0.0000	cm
Ring 2 elements pitch circle diameter	2.9769	cm
Ring 3 elements pitch circle diameter	5.7506	cm
Ring 4 (outer) elements pitch circle diameter	8.6614	cm
Element (sheath) outside diameter	1.31	cm
Average sheath wall thickness	0.04	cm
UO_2 pellet outside diameter	1.22	cm
Stack length	48.20	cm
UO_2 density	10.62	g/cm^3
UO_2 weight per bundle	21.782	kg
U weight per bundle	19.136	kg
Maximum linear bundle rating for bundle power of 800 kW	16.15	kW/cm
Nominal operating fuel temperature	687.0	ºC
Moderator density	1.0851	g/cm^3
Coolant density	0.8079	g/cm^3
Nominal operating moderator poison concentration	0.0	ppm

Table 2 Vertical Stainless Steel Adjuster Incremental Cross Sections for an Equilibrium Core

Adjuster Type	$\Delta\Sigma_{a2}$ ($cm^{-1}\times10^{-3}$)
A-Inner	0.60716
A-Outer	0.52446
B	0.89669
C-Inner	0.81852
C-Outer	0.36311
D	0.50885

Table 3 Vertical Liquid Zone Control Incremental Cross Sections for an Equilibrium Core

Zone Control Compartment	$\Delta\Sigma_{a2}$ ($cm^{-1}\times10^{-3}$)
1, 4, 6, 8, 11, 13 (21)	
Empty	0.17110
Full minus Empty	1.1086
2, 5, 7, 9, 12, 14 (10)	
Empty	0.09617
Full minus Empty	1.2203
3, 10 (32)	
Empty	0.24870
Full minus Empty	0.99349

Table 4 Vertical Shutoff-Rod and Mechanical Control Absorber Incremental Cross Sections for an Equilibrium Core

$\Delta\Sigma_{a2}$ ($cm^{-1}\times10^{-2}$)
0.48995

Table 5 Guide Tube Incremental Cross Sections for an Equilibrium Core

Tube Type	$\Delta\Sigma_{a2}$ ($cm^{-1}\times10^{-5}$)
Vertical Tubes:	
Adjuster	1.4802
Zone Control Unit Bottom	2.5778
SOR/MCA	2.4706
VFD	0.61690
Horizontal Tubes:	
HFD	0.62300
Liquid Poison Injection Nozzle	3.6329

Table 6 Structural Material Incremental Cross Sections for an Equilibrium Core

Structural Material Type	$\Delta\Sigma_{a2}$ ($cm^{-1}\times10^{-3}$)
Vertical Material:	
Adjuster-Specific Material:	
Adjuster Support Bar	0.032187
Adjuster Support Cable	0.012815
Tensioning Spring:	
Adjuster	2.4984
SOR/MCA	3.7150
Zone Control Unit	3.2996
Coupling Nut:	
Adjuster	3.0853
SOR/MCA	4.6777
Zone Control Unit	4.2082
Bracket and Locator:	
Adjuster, SOR/MCA, Zone Control Unit, VFD	2.1971
Other:	
Moderator Inlet Nozzle Deflector	3.1149
Horizontal Material:	
Bracket and Locator:	
HFD and Liquid Poison Injection Nozzle	2.1971

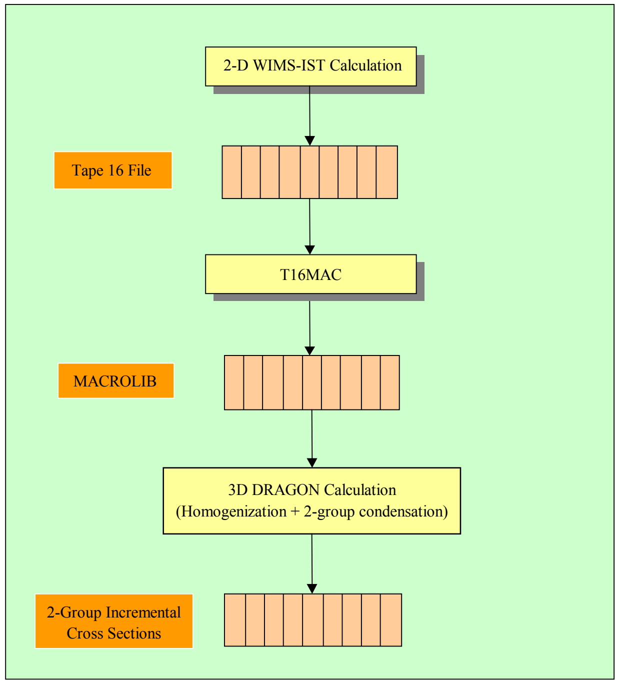
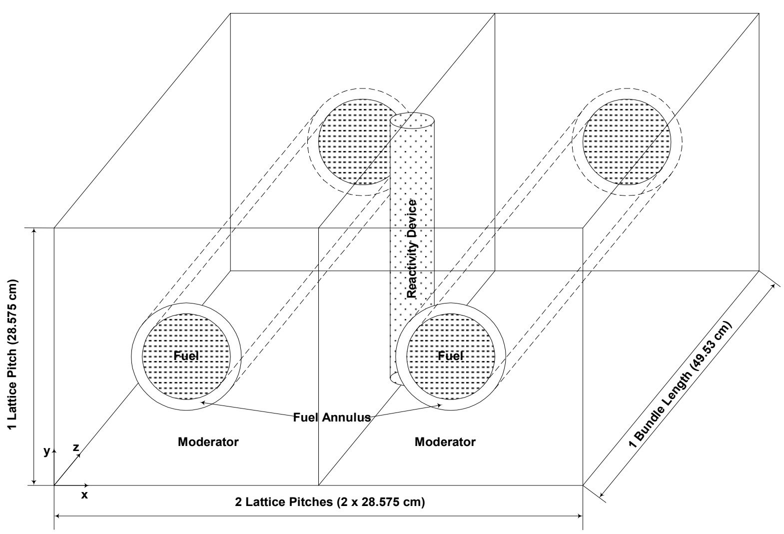


Figure 1 Schematic of Side-Step Method for Calculating Incremental Cross Sections



Boundary Conditions:

X_- Reflection	X_+ Reflection
Y_- Reflection	Y_+ Reflection
Z_- Reflection	Z_+ Reflection

Figure 2 Typical Supercell Model in DRAGON-IST

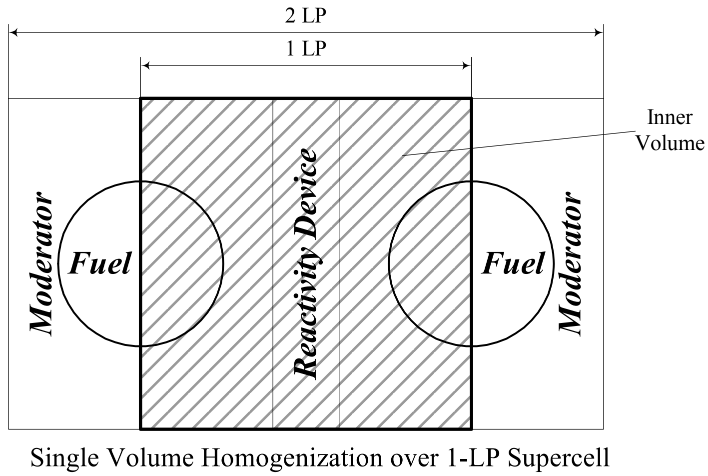


Figure 3 Supercell Homogenization

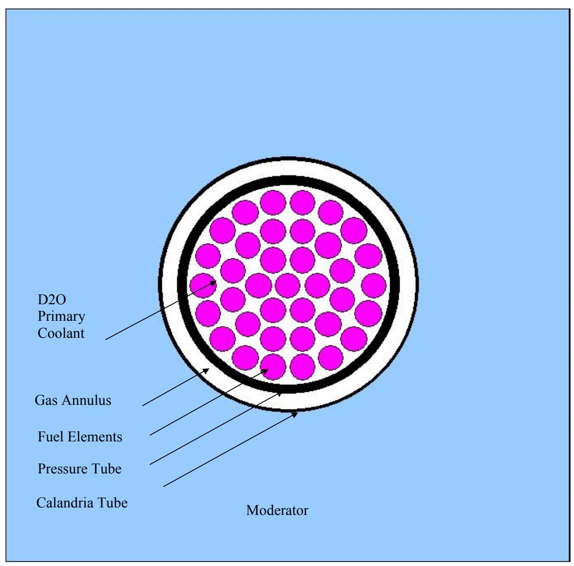


Figure 4 Typical 37-Element Fuel CANDU Cell

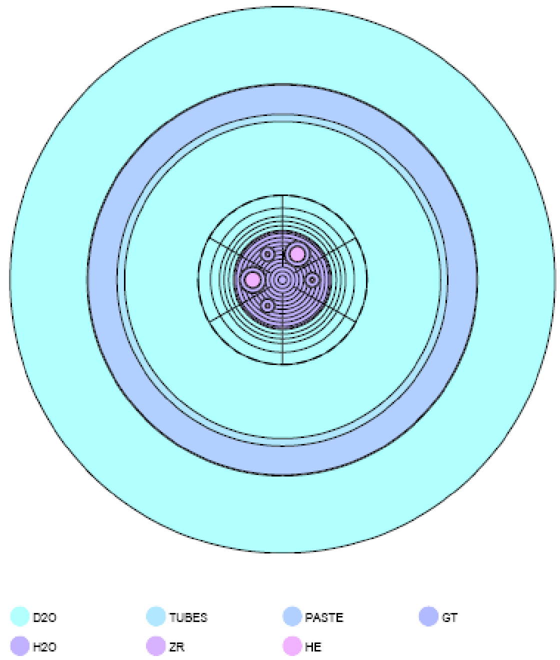


Figure 5 WIMS-IST Model for the LZCU

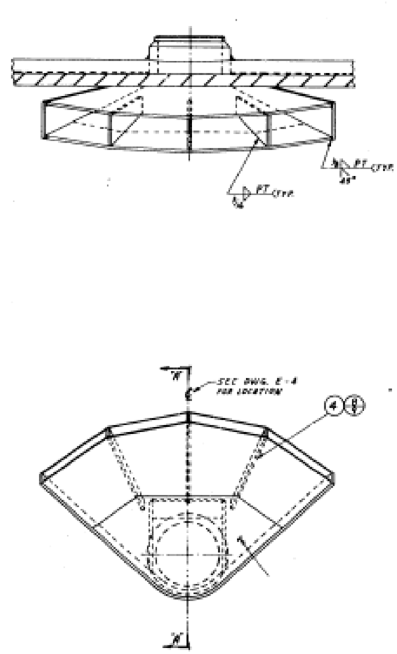


Figure 6 Moderator Inlet Nozzle Deflector